DARPA Emerging Technologies

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Abstract

Current research at the Defense Advanced Research Projects Agency (DARPA) investigates the realm of the possible and provides insight into future force structures. DARPA is pursuing critical breakthrough technologies to enable a dispersion of assets while maintaining concentrated effects. In particular, this article presents breakthrough research in disaggregated capabilities, hypersonic strike weapons, and directed energy. These capabilities will be essential for operations in anti-access/area-denial (A2/AD) regions and offer to replace the monolithic manned platforms with a network of integrated systems disaggregated across teams of manned and unmanned air vehicles. Coupled with hypersonic standoff-strike munitions and enhanced directed-energy capabilities, these technologies provide a viable option for maintaining a credible global strike capability.

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Maintaining a strong military pillar of national power by providing a credible ability to hold adversaries at risk while protecting US interests is vitally important to achieve national strategic objectives. In most conceivable future conflicts, the only certainty is the existence of complex threats. Some of the emerging technologies currently in development at DARPA can mitigate these threats.

DARPA's mission is to make pivotal investments in breakthrough technologies for national security. Toward that end, the agency has focused on critical technological areas and developed a vision of what may be required to remain viable against emerging threats. The design space in which DARPA operates is quite vast. As an aspirational aphorism,

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DARPA quotes Franz Liszt, who intoned the following raison d'être, "To cast a javelin into the infinite spaces of the future." To ensure a less than infinite scope, this article will focus on three areas that are most critical in the air domain against complex, layered integrated air defense systems. This environment is part of the more broadly described concept of anti-access/area-denial (A2/AD) and provides a defining system stressing strategic challenge for future force structures. Of the many mission areas that could be explored to provide access to A2/AD environments, three seem particularly promising:

1. saturating the A2/AD environment with multitudes of low-cost, networked vehicles that provide disaggregated capabilities;
2. staying outside the denied area and systematically rolling back enemy air defenses by launching standoff weapons that are very high speed (hypersonic), maneuverable, and reasonably survivable against projected defenses; and
3. pursuing advancements in high-energy lasers that provide defensive and offensive technologies enhancing platform survivability while imposing costs on the adversary.

A successful combined arms strategy contains elements of each of these areas.[1] Even if these capabilities are never exercised, the investment bolsters the US ability to influence international affairs. Indeed, a truly successful national defense strategy achieves its ends without ever firing a shot. Examining progress in these areas influences technology to provide material solutions to proliferating geopolitical challenges. Only through consistent investment and persistent effort will developments in disaggregated network capabilities, hypersonic strike vehicles, and directed energy provide a credible capability to hold adversaries at risk, bolstering the military pillar of national power and protecting future American strategic interests.[2]

Disaggregated Capabilities

Using technological superiority to protect human life is a hallmark of US military culture. As a result, the trend in Air Force acquisitions has been toward ever more expensive manned platforms that have increased in size and complexity to address the increasing demands of the modern battlespace. In light of finite resources, the increased unit costs of these

large capital assets have led to a corresponding decrease in quantity. Today, in light of constrained budgets, rising economic near-peer states and global uncertainty that demands agility, this trend is unsustainable. Since quantity is a key enabler of geographic flexibility, providing quantity at a reasonable price requires a radical shift in this single platform based allocation of resources.

As early as 1982, aerospace businessman Norman Augustine identified a trend in defense acquisition that showed that defense budgets grow linearly, but the unit cost of new military aircraft is growing exponentially. Augustine humorously quipped, "In the year 2054, the entire defense budget will purchase just one tactical aircraft. This aircraft will have to be shared by the Air Force and Navy 3½ days each per week except for leap year, when it will be made available to the Marines for the extra day."[3] This very real trend limits operational flexibility, since small numbers of aircraft cannot be in multiple locations at the same time. Furthermore, antiaircraft defenses are becoming so advanced that spending more to produce the most effective strike aircraft does not reasonably ensure its survival. With these pressures in mind, a paradigm shift is necessary. This shift is sometimes described as the third offset strategy. Deputy Secretary of Defense Robert Work clarified five key building blocks for the third offset strategy in policy speeches in late 2015.[4] These building blocks are as follows:

1. autonomous machine learning,
2. human-machine collaboration,
3. assisted human operations,
4. advanced human-machine combat teaming, and
5. network-enabled, cyber-hardened, semiautonomous capabilities.

Putting these building blocks together in the air domain leads to a new system-based force architecture. In this vision, teams of manned and unmanned systems provide military utility, cost imposition to the adversary, and adaptability through the use of disaggregated network capabilities. Spreading out capabilities across multiple network-linked platforms, rather than concentrating all functions on a single expensive platform, enhances flexibility, scalability, and specialization. As a first step, the term *disaggregated* is appropriate because it shows a clear delineation from legacy monolithic single-platform-based aggregated

capabilities. As this concept matures, however, and new capabilities are added to the network that would not have existed on current platforms, *distributed capabilities* is perhaps the more appropriate term. Since this article speaks primarily to the transition period, these terms are used interchangeably. Critical challenges of disaggregated systems include platform development; human-machine interfaces; secure, reliable network communication; and overall system architecture/command and control. Within DARPA this concept is called a system-of-systems approach, and one such concept for disaggregated capabilities is shown in figure 1.

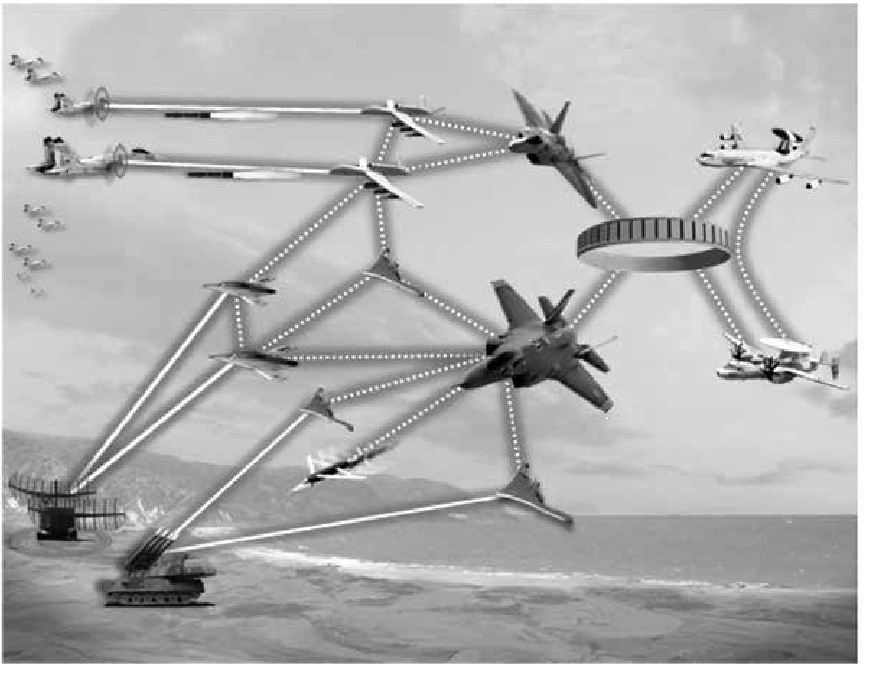

Figure 1. Distributed capabilities. (Image courtesy of DARPA's Strategic Technologies Office.)

The following pages address three current DARPA efforts that seek to leverage advantages of distributed capabilities using the building blocks of the third offset strategy while addressing the critical challenges: (1) the Gremlins program provides low-cost unmanned platforms that are geographically flexible, (2) the Aircrew Labor In-Cockpit Automation System (ALIAS) program lays the groundwork for more effective human-machine collaboration through machine learning and enhanced human-system interfaces (HSI), and (3) the Collaborative Operations in Denied Environments (CODE) program builds the algorithms for human-machine teaming and semiautonomous collaboration.

The Gremlins Program

Building effective systems that do not require a person in the cockpit can help reimagine the cost equation and create less expensive systems in larger quantities. Not only does this address the need for geographic agility but it also provides a viable solution for the challenges of the A2/AD environment. Though these systems may not be able to survive a complex air defense environment individually, in large quantities they may be able to saturate an adversary's engagement capability. Low-cost, attritable unmanned aerial vehicles (UAV) operating in cooperative packs can prosecute complex missions in high-threat environments without putting US pilots at risk. Furthermore, this can be accomplished in a cost-imposing fashion. For example, if a UAV costs less than the missiles required to defend against it, this is a cost imposition on the adversary. The goal, therefore, is to build systems that are lethal enough that they cannot be ignored but inexpensive enough that the loss of an individual vehicle is acceptable. As a new DARPA program, Gremlins is a system of unmanned platforms that seek to avoid the high costs of life support and complex defensive capabilities normally required of manned aircraft.[5]

Figure 2. DARPA Gremlins. (Image courtesy of DARPA's Tactical Technology Office.)

Gremlins are UAVs conceived to be air-launched and air-recoverable in volley quantities. This provides the platforms needed to constitute a cooperative pack of capabilities to prosecute various missions. However, to keep costs low, these vehicles must be relatively small, which means

their range is limited. To overcome this challenge, the Gremlins program leverages a larger host aircraft to take the Gremlin fleet to the edge of the contested area before launch. Because the Gremlin air vehicles (GAV) are recoverable rather than expendable; the per-use costs are much lower than for a cruise missile or traditional decoy.[6] Mission success is defined as meeting objectives with a specified percentage or less of the individual munitions or vehicles being destroyed along the way.

GAVs could be launched from a wide array of aircraft, including bombers, fighters, and cargo aircraft. A notional approach, and the flight demo planned for the Gremlins program, leverages air recovery into an aircraft with a cargo bay. The most challenging technical risk of this project is solving the problem of air recovery without endangering the host. GAV air recovery is still in development, but designs focus on three critical capture phases:

1. soft capture outside of the highly turbulent region directly aft of the host aircraft using precision navigation techniques demonstrated through previous UAV air-refueling programs;
2. hard capture into a structure that provide six degrees of freedom restraint for transition through the turbulent region aft of the host. This phase leverages advances in robotics. Of note in this phase, GAV aerodynamic surfaces will retract, and the engine will be shut off and inserted to protect the host aircraft; and
3. transition into the cargo bay and automated rack storage of volley quantities of GAVs.

The demonstration goal is to recover four vehicles every 30 minutes. Once air recovery is successfully demonstrated, various air vehicles could be developed to address specific mission needs. The Gremlins' objective system is roughly the size of a cruise missile and has the following design goals shown in table 1.

GAVs are large enough to carry relevant electro-optical sensors for intelligence, surveillance, and reconnaissance (ISR) and for target identification, with enough onboard power for electronic attack. As needed, they could carry a warhead with enough destructive power to engage semihardened targets.

Table 1: Gremlins air vehicle key performance parameters

	Threshold	Goal
Design radius	300 nm	500nm
Design loiter time at design radius	1 hr	3 hr
Design payload	60 lb	120 lb
Maximum one-way range, no loiter	Fallout from system design	
Loiter time for recovery	As needed	
Maximum speed	Mach 0.7	Mach 0.8+
Max launch altitude	not specified	40,000 ft + (compatible with launch from many aircraft
Propulsion system	Objective system may be designed with conceptual design engine model (at existing technology level), or existing propulsion system, or modified propulsion system (e.g., addition of fan stage).	
Payload power	800 Watt	1200 Watt
Payload installation	not specified	Side and fore/down-facing aperture provisions
Payload type	Modular, with provisions for depot-level change–out among various payloads, including radio-frequency (RF) payloads and electro-optical infrared (EO/IR) payloads, among others. Assume typical RF payload power density to determine payload size/volume requirements.	
Design life	not specified	20 uses
Gremlin air vehicle recurring (flyaway) cost, exclusive of mission payloads	$700 K (FY15)	Minimal cost
Gremlin system-level metrics		
Host launch platforms	B-52, B-1, C-130	As many aircraft as possible, including tactical (fighter)
Launch quantity	8 or more per host	20+ for large aircraft host
Host recovery aircraft	C-130	
Recovery quantity and timeline	≥4 Gremlins recovering in <30 min; goal to be capable of recovering 8 or more in total.	
Probability of successful recovery	≥0.95 within time window	
Probability of host (launch or recovery) aircraft loss due to gremlins operations	not specified	<1x10^-7 incidents per flying hour
Recovery and refurbishment cycle	<24 hours from recovery to refit onto aircraft for launch, with minimal manpower and personnel costs. Fit within USAF structure for maintenance/checkout at forward operating base.	
Host system equipment, recurring (flyaway) cost, exclusive of command/control system costs.	$10 M (FY15)	$2 M or less (FY15)

Payload and power requirements were set by a number of other DARPA programs, ranging from coherent jamming to advanced cooperative syn-

thetic aperture radar mapping to electronic attack with cyber effects. For many of these radio frequency–domain effects, speed is a key enabler. At Mach 0.7+ the objective system is fast relative to existing UAVs, enabling flexibility in payload employment. High speed also allows the vehicles to potentially team with other strike assets or fly ahead of special operations infiltration/exfiltration teams. Survivability is also enhanced by speed and altitude capabilities that remove the vehicle from traditional small arms and man-portable surface-to-air missile weapons engagement zones. Small size naturally enhances low observable characteristics, and this will be a design consideration for future weapons systems.

Air launch and recovery directly addresses several critical challenges of global agility. First, it offers global access and rapid response. The US military currently enjoys freedom of movement throughout most of the world's airspace. With existing global mobility assets, Gremlins launching from bases within the continental United States (CONUS) could be employed anywhere in the world within 36 hours. Corollary to this is no dependence on vicinity basing. Current UAVs are slow and require significant infrastructure directly in the region of interest. This is unrealistic in emergent scenarios in regions where we have little forward basing or in A2/AD environments where we may not have land or sea control close to our objectives. Air recovery offers fast cycle time. The vehicles may be refueled, serviced, and ready to fly again quite rapidly.

GAVs offer a compelling solution to the platform challenge in creating disaggregated capabilities. Air launch and recovery of sophisticated unmanned assets enables scalability and diverse effects in a fiscally efficient manner. Though the focus here is on saturation-layered defenses as the most challenging use case, disaggregated network-based capabilities also allow a more efficient use of resources across the spectrum of conflict. When relying on platform quality rather than quantity, that expensive platform is underutilized when employed in less-demanding environments. For example, using a B-2 to strike an undefended adversary's pickup truck is certainly fiscally inefficient. Disaggregated low-cost platforms use quantity to scale to the requirements of the scenario. In the most demanding case, more platforms saturate defenses. In less challenging scenarios, fewer platforms can be employed. In this way, capabilities utilization is better matched to mission requirements. When facing economically near-peer adversaries, cost efficiency is a necessary strategic consideration.

Platform development is only one piece of the challenge in creating disaggregated capabilities. Also critical is effectively interfacing with the human mind directing these assets. Toward that end, DARPA is pushing the realm of the possible in human-machine collaboration and machine learning through the ALIAS program.

Aircrew Labor In-Cockpit Automation System

ALIAS seeks to develop and insert new automation into existing aircraft to increase mission effectiveness and safety while enabling operations with reduced onboard crew.[7] To achieve this goal, the program is dramatically pushing the frontiers of machine-learning capabilities and developing robust methods for human-machine collaboration. The system is designed to be quickly transferable from vehicle to vehicle, requiring rapid knowledge application and flexible implementation. As such, the core problem-solving algorithms being developed to meet this program's requirements will likely have broad applicability in autonomous and semiautonomous operations. The way a future operator will interface with the cooperative packs will likely be a derivative of this program. The way future vehicles solve mission challenges with a man in the loop or autonomously will likely be based on the ALIAS computational core. This is a whole new realm of possibility, and ALIAS is an important first step.

The heart of the ALIAS program is the intelligent processing core that provides flight management and system analysis. Information is fed to the system through a knowledge acquisition system that uses real language processing to digest normal text and subdivide it into a logical framework that can be queried by the core. In this way, the machine can quickly acquire all printed knowledge on a topic and learn the exact procedures for conducting myriad flight maneuvers. The system also can be taught by an expert human demonstrator and will internalize that lesson. Data quality will be prioritized, and a human subject-matter expert can resolve discrepancies. The ability to rapidly acquire and codify diverse data sets is truly revolutionary and has application far beyond the scope of this program. One can imagine using the process devised through this program to streamline ISR data analysis or develop real-time command-and-control suggestions based on application of operational doctrine. Within the scope of the current program, the system will provide robust analysis of mission and flight contingencies. The

ALIAS system can analyze options and provide aircrews with feedback on mission impacts. In this way, the crew acts as a mission coordinator focused on high-level execution—rather than being technicians. In addition, the core will be able to deal with system contingencies such as an engine failure. It would pull up appropriate checklists, possibly actuate switches, and define mission impacts, providing the crew with options.

The ALIAS program is also developing a perception system. ALIAS is intended to be an ultimate state machine—a machine that can simulate any computer algorithm, no matter how complicated—that measures and monitors all critical mission elements like airspeed, altitude, fuel state, location, subsystem status, mission intent, and vehicle performance. This can be done through internal cameras reading gauges and dials and switch positions, directly tapping into current or future avionics service buses and integrating datalink signals or external cameras.

A revolutionary step this program is taking is including the human operator as a parameter in the human-machine state. To this end, cameras may be used to track pilot posture and reactions, control actuation could be measured to gauge pilot attentiveness, and, in one intriguing application, pilot brain waves could be directly monitored in flight using electroencephalography (EEG) sensors integrated into the pilot's headset or helmet. This concept builds on the work from a DARPA-funded effort entitled BrainFlight, which used active brain monitoring in flight to measure workload and predict pilot-induced oscillations. Building on a host of successful brain-monitoring programs brings enormous potential to more directly interface the human brain with machines. Employing EEG as an input to the ALIAS perception system is an exciting step toward tapping into that potential. At a minimum, monitoring the pilot's performance will give the system key information allowing it to recognize if the human is fatigued or overloaded or missed an alert. As a result, there may be more effective two-way communication between the ALIAS system and the human operator.

Finally, the ALIAS system eventually will be able to fly aircraft, move switches, and perform operations just as a human could. Because the system is intended to be portable from aircraft to aircraft, actuation concepts are typically kit-based with slightly different implementations based on the constraints of the aircraft involved. The kit could consist of various mechanical switch actuators, robotic elements, direct mechanical linkages to flight controls, direct electrical interfaces into the buses,

or other similar devices. No single actuation system will work in all aircraft; thus, a suite of solutions will be available. Notably, flight control applications are being built with the high level of reliability and redundancy one would see in a digital flight-control system. Unlike a typical autopilot that is built with single path failure modes that require the human to take over in contingency situations, the ALIAS flight-control actuators are triple redundant, providing extremely high reliability. Beyond being just a better autopilot, ALIAS could prove to be at least as reliable as a human operator, enabling a major technical leap forward.

ALIAS is addressing head-on the somewhat nebulous concept of human-machine teaming. Typical pilot/copilot functions are not directly transferable to an optimal human-machine team. Humans excel at certain functions, such as applying tactics and building strategy, and machines transcend in other realms, such as routine station keeping and rapid computation. ALIAS provides a platform to redefine typical crew roles to provide an even more effective team. Furthermore, ALIAS may enable human operators to work outside their own cockpit. As operating their own vehicle is simplified, they could have capacity to cooperatively direct other vehicles. In the future, humans may work alongside unmanned semiautonomous wingmen and strike vehicles. Working with these disaggregated assets requires algorithms that translate human intent into coordinated semiautonomous action. This is made even more difficult since future wars may likely be fought in radio-frequency and GPS-contested environments. Human-machine teaming and semiautonomous collaboration in contested environments are critical capabilities and are central concepts in DARPA's Collaborative Operations in Denied Environments (CODE) program.

Collaborative Operations in Denied Environments

CODE seeks to develop advanced autonomy algorithms and supervisory control techniques to enhance the capability of UAVs or sophisticated missiles in denied environments.[8] This is addressed through four major technical areas: (1) collaborative autonomy, (2) vehicle-level autonomy, (3) supervisory interface, and (4) open architecture for distributed systems. Key technological advancements focus on autonomous collaboration for sensing, strike, communication, and navigation, reducing required communication bandwidth and HSI. These goals are being pursued through simulations and software development currently

and aim to culminate in a large flight demo using live and virtual assets in a GPS- and communications-denied environment.

Collaborative autonomy is a somewhat vague term, but perhaps some specific examples will clarify its meaning. Imagine a dozen cruise missiles deep in enemy territory looking for a mobile surface-to-air missile (SAM) site. One could assign each missile independently a search/kill box and hope to find and destroy the SAM in this way. Using collaboration instead, the cruise missile pack could set up a coordinated search grid, notify other missiles of targets of interest, and bring multiple sensors and azimuths to bear to increase the probability of accurate target identification. Adding to this scenario, assume GPS is not available—removing a trusted outside navigational source. This makes accurate positioning and targeting difficult. Within a collaborative network, relative position can be determined. Using known landmarks or a single navigational beacon, the entire pack of missiles can update their position. In this example, absolute position is not that important. Known relative position to the target is sufficient to close the kill chain. Once a target is identified, the cruise missiles could encircle the target and strike simultaneously, overwhelming any missile defense systems in place. Collaboration allows for greatly increased effectiveness and efficiency, allowing the salvo size to be reduced. This effects-based thinking preserves resources while optimizing mission success.

Another important aspect of collaboration is coherent radio-frequency effects. Multiple platforms with very accurate clocks can transmit waveforms that combine constructively. It turns out that combining waveforms in this way actually scales via a square of the number of platforms rather than just being additive. Hence, coherently combining signals from four collaborative platforms can provide up to 16 times the broadcast power. Coherently combining even larger numbers of signals can be immensely powerful, yielding significant increases in detection and communication range or enabling burn through of enemy jamming.

Efficient use of available bandwidth is vital to collaboration in a challenging RF environment. The objective is to maintain a common situational awareness picture across the team. This is done by decreasing the information each vehicle needs to know about the state of other vehicles through behavior and health modeling. For example, rather than sending constant updates on how much fuel a vehicle has on board, each member of the team can calculate how much fuel it expects its team members to have based on an internal model. Therefore, updates to fuel

status could be very infrequent or only happen when actual fuel levels diverge from model expectations. Information that must be passed is assigned a value and is compressed based on what is important for that specific mission engagement. Early studies show this to be extremely effective over time, reducing the bandwidth required by a factor of 20.

Large numbers of semiautonomous vehicles under the control of a human mission commander demand a new vision for the HSI. The core challenge is interacting with dozens of UAVs in intermittently denied communications environments. Even under high workload, the human operator must be able to maintain situational awareness. High-functioning autonomy must be employed in an informed manner without sacrificing appropriate human oversight and control. At the same time, autonomous vehicles must react reliably and consistently, building operator trust. On the spectrum of human to remote vehicle control, one extreme would be the General Atomics MQ-1 Predator UAV, where a human pilot directly controls all flight functions. A more viable model for the future is applying the notion of commander's intent. Packs of UAVs could be sent out with clearly defined objectives and prosecute that mission autonomously even if severed from communication with the mission commander. In accordance with the rules of engagement, the commander would be notified before predefined actions were authorized, such as a weapon's release or crossing a geographic border. At the same time, relevant data should be presented to the human mission commander so he or she can make reasoned decisions. Porting raw data from so many sensors back to the human would be overwhelming. Instead, specific actionable information that shows behavior over time and mission relevant trends builds optimal situational awareness. There is a rich heritage of command and control using dispersed human teams. This can serve as a starting point for developing human-machine teams. However, ultimately the allocation of labor should leverage inherent human and machine strengths rather than blindly following old models of behavior simply because they are familiar. CODE is exploring a suite of mission planning tools and interfaces to overcome these challenges and provide the right level of information to humans, allowing them to exert the right level of control over the machines. Figuring out this "Goldilocks" zone is a major thrust of the program's research.

Open-system architecture is critical to development of the CODE communication backbone. Legacy systems and new designs not yet

built must be able to operate together in an environment that allows for continuous improvement. This is enabled by providing all players with clearly defined, government-owned interfaces allowing rapid integration, adaptability, and flexibility in testing. Open architecture is a design commitment that must be built into the system at every step of the way. However, given the goal of allowing collaboration between many different assets, it is essential to the CODE vision.

A host of programs in development aim to support network-based disaggregated capabilities. The programs that enhance overall capabilities but are not critical to the vision should be consistently researched. Predictability in programmatics is the key to efficient design, prototyping, and testing. Sudden surges and crashes in execution lead to erratic schedules that increase costs. Most importantly, this unpredictability makes talent management difficult. Innovation comes from enabling and resourcing brilliant people and granting them the freedom to explore new ideas. Innovative development takes time. Scientific breakthroughs are not predictable. As such, overall system maturation should be given the best chance to succeed through a steady research program that retains talented individuals over time.

Several theaters that present A2/AD challenges due to their integrated air defenses are also vast geographic regions with limited opportunities for US forward basing. As a result, long-range platforms are vitally important to future power projection. For example, B-21s must be purchased in significant quantity to support operational flexibility. The range limits of tactical fighters must be addressed and careful thought put into the logistical tail. Often, future battle scenarios are conceived with dozens of fifth-generation fighters and strike aircraft magically ready to penetrate the densest part of the A2/AD environment. Weapon detection and engagement zones are significantly wider for large aircraft, often denying the ability to have tanker support close enough for tactical fighters or traditional UAVs to be relevant. Future research should explore increasing tanker survivability to allow them to approach the forward edge of the battle. Nontraditional UAVs such as Gremlins launched by traditional long-range mobility platforms provide another viable option. Even if efforts are able to secure some forward basing options, priority must be given to platforms with range and penetration ability. Scenarios with quantities of tactical range fighters or traditional UAVs must be met with skepticism. It is time to ask the hard questions

of how they get there. If the answer is air refueling and 20-hour duty days for the pilots in tactical, single-seat cockpits, that inflicts a serious human toll on performance and regeneration time. Air dominance in contested environments will require long-range manned platform hosts teaming with attritable tactical UAV partners that are not subject to fatigue. Even the term "fighter" may be antiquated, conjuring thoughts of small, highly maneuverable dogfighters. In the future battlespace, envisioning these platforms as manned nodes or sensor/shooters may be more informative.[9] Focused research should continue to develop long-range, manned control platforms.

The Strategic Technology Office at DARPA has committed itself to a system-of-systems approach out of necessity, but this also allows the agency to seize inherent opportunities. Fielding a force capable of defeating future adversaries at a price the American public can afford is a driving factor. This approach uses architectures networking unmanned, lower-cost, lower-capability platforms with optionally manned, higher-cost, higher-capability platforms. The lower-cost platforms are able to enhance the military effectiveness and survivability of higher-cost platforms while protecting the human in the force. Different types of platforms limit systemwide vulnerabilities. The lower-cost platforms can be bought in enough quantity that they can saturate defenses: Quantity becomes a quality of its own. This seizes initiative by imposing complexity and cost on the adversary. Open architecture and less investment risk enable quick innovation and development of the lower-cost platforms. New vehicles, sensors, and systems that are peripheral to the command-and-control core could be adapted quickly with little risk to the overall system.

The future A2/AD battlespace is layered and complex. Current platform-based strategies likely cannot achieve air dominance in this environment and are financially unsustainable. A radical shift to network-based system-of-systems approach can overcome these challenges. DARPA's investment in Gremlins, ALIAS, and CODE is paving the path toward a possible future. As a research organization, DARPA can only take this vision so far. For it to become a reality, the services must take up the torch and develop programs of record that support these efforts. Air Force senior leaders have repeatedly stated their commitment to this vision. However, overcoming years of inertia at lower levels will require sustained pressure.

Hypersonic Strike Weapons

A second way of dealing with an A2/AD environment is to use long-range standoff weapons that allow platforms to strike within the protected space without actually penetrating it themselves. Hypersonic flight is a vitally important and inevitable revolution in aerospace power based on a suite of technologies currently in development in the United States and abroad. Though routine manned hypersonic air vehicles are likely still several decades away, hypersonic strike weapons will be operational much sooner. Hypersonic flight generally refers to vehicles travelling in excess of Mach 5, roughly 3,600 miles per hour or one mile per second. While vehicles in this class face significant technical challenges due to extreme temperatures and thermal loadings and complex aerodynamic effects, they also potentially enjoy significant tactical advantages. By carefully considering the benefits and challenges of hypersonic vehicles and looking at current developmental projects, one can chart the proper course toward realization of hypersonic strike vehicles that will fundamentally alter the technical means of power projection.

Advances in infrared search and track and full-spectrum radar effectively deny penetration into certain regions for most platforms. Hypersonic standoff strike seeks to return the advantage to the attacker by holding targets at risk without endangering the launch platform. In addition, speeds in excess of one mile per second could enable unprecedented rapid response and flexibility. A single platform launching a volley of hypersonic strike weapons could simultaneously strike targets a thousand miles apart in less than 10 minutes from launch. This would allow commanders to penetrate an adversary's decision cycle, striking before they are able to orient and act. Rapid action is particularly critical when dealing with mobile targets or when leveraging surprise. Countering the tyranny of geography that vast regions present, hypersonic weapons shrink the flight time to targets, granting tactical agility. Rapid strike is a key component of Air Force doctrine, and hypersonic strike significantly extends the reach and lethality available to commanders.

A B-52 loaded with dozens of hypersonic strike weapons could effectively contribute in even the most defended environments by launching standoff weapons outside of the enemy's engagement zones. By enabling legacy platforms to participate in this "high-end" fight, the commander would gain significant flexibility. Developing weapons sized for launch from tactical platforms would further expand options available to com-

manders. True radar penetrators like the B-2 are extremely limited in quantity, which limits flexibility to respond in multiple regions. Furthermore, it is more cost-effective to invest in expendable weapons in quantities that achieve power-projection goals rather than purchasing large numbers of expensive platforms. This is not to say that these expensive platforms in some number are not necessary. However, leveraging significant standoff-strike capabilities reduces the number of penetrating platforms needed, a reality in a time of limited budgets. Finally, even the best low-observable technology is only as good as the next defensive advancement. Already, full-spectrum search and track limits the utility of our stealth platforms. As the never-ending, cat-and-mouse game between attackers and air defenses continues, having a potent standoff capability could provide an important insurance measure.

The hypersonic environment is epically hostile, resulting in significant technical challenges. At these speeds, gas molecules begin to disassociate, producing an ionized plasma around the vehicle. Sonic shock waves fold close to the body of the vehicle with strong entropy gradients creating flows that disturb the boundary layer. While understanding the physics of this is not essential to this discussion, it is important to note that many of the aerodynamic and thermodynamic models that have been developed over years of flying supersonic vehicles no longer apply in the hypersonic realm. Furthermore, kinematic heating is extreme, and slight miscalculations quickly lead to destructive melting and structural burn through. In the case of scramjet vehicles, fuel must be mixed and ignited with a supersonic flow of air in milliseconds. The analogy of lighting and sustaining a candle in a tornado is apt. At this point, many of these fundamental issues have been overcome by previous development programs expanding the knowledge base of hypersonic flight controls and thermodynamics. The next step for hypersonic strike weapons is building a reliable platform at a tactically relevant, affordable, expendable weapons price point. Further consideration for weaponizing a hypersonic vehicle will need to focus on communication, targeting sensors, affordable high-temperature materials, manufacturing methods, and operational concepts.

Other nations are pursuing hypersonic technologies also. For example, India is close to fielding the BrahMos-II, a hypersonic cruise missile (figure 3). Soon, hypersonic strike weapons will be a reality in the battlespace, and many of those weapons will be in the hands of potential

adversaries. This underscores the importance of continued US development and highlights a corollary imperative: For many of the reasons already discussed, hypersonic weapons can be very difficult to defend against. Efforts must be made to understand adversary systems and develop effective defense strategies to mitigate potential threats. Simply winning the race to field the first hypersonic strike weapon does not address this future vulnerability.

Figure 3. India's BrahMos II hypersonic cruise missile. ("Model missiles BrahMos-II exhibition DefExpo-2014," *Defense and Aerospace News* [India], 5 February 2014.)

The Mitchell Institute for Aerospace Studies lays out key steps for the path forward in hypersonics based on a consistent and disciplined technology path.[10] The history of hypersonics is littered with exciting projects that overreached and failed, often spectacularly. Recent efforts such as the X-51A Waverider (figure 4) have been successful by setting more moderate, achievable goals and consistently advancing the state of the art. Continued work at DARPA and the Air Force Research Laboratory (AFRL) builds on that success and paves the way toward realizable fielded systems. To reach this goal, consistent research must continue in these programs—including developing adequate test and research facilities. Hypersonic technology development requires wind tunnels and ranges that do not currently exist. Furthermore, continued technology maturation is needed for thermal management, materials and structures, and hypersonic flight controls and propulsion. Hypersonic weapons are no

longer the stuff of science fiction. They will be here sooner than most people realize. These weapons offer a significant asymmetric advantage and must be considered in any future strategy. Ensuring the United States seizes this advantage requires awareness of the potential, a future operational vision, and consistent rigorous research.

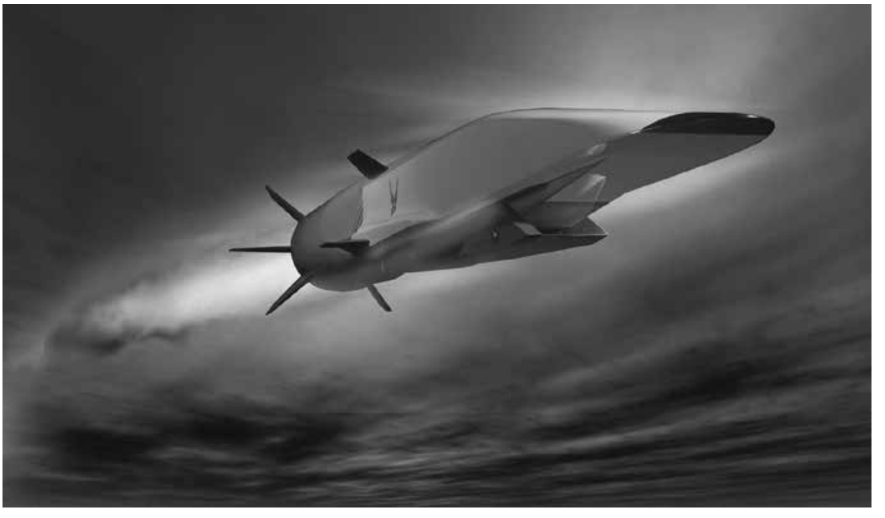

Figure 4. X-51A WaveRider. (United States Air Force, "X-51A WaveRider," http://www.af.mil/shared/media/photodb/photos/100520-F-9999B-111.jpg, accessed 20 May 2010.)

Directed Energy

One of the most disruptive trends of the last half century has been the steady rise of ubiquitous microelectronics. In the military realm this presents a significant challenge and an opportunity. Proliferation of emerging seeker technology threatens current aircraft defenses while corresponding advances in laser technology promise to deliver reliable high-energy lasers. This provides revolutionary new military capabilities countering next-generation sensors and creating offensive laser weapons. High-energy airborne lasers are a logical next step in aircraft defense and an important future offensive strike capability.

In the past, chemical lasers were the only laser option with enough power density to deliver a militarily significant beam in a size- and weight-limited environment. However, significant progress has been made over the past decade using fiber lasers. These solid-state lasers are more robust, more compact, and more suitable for a military environment than their chemical predecessors. A single fiber laser starts with electrical energy that is converted to high-power, high-beam-quality laser energy.

Because the created beam is then contained in a fiber-optic cable, it can be transmitted flexibly and combined to create a beam of military significance.[11] Progress in fiber laser arrays, beam combination, and adaptive optics promises a future in high-energy lasers that is indeed very bright, with laser power perhaps on the order of hundreds of kilowatts.

Advanced imaging circuits, particularly focal-plane array sensors, present a significant threat to airborne platforms.[12] These advanced seeker heads are an immediate threat to air vehicles that high-energy lasers can address, and the threat demands a new paradigm in aircraft defense. Due to size, weight, and power considerations, large aircraft using next-generation high-power fiber lasers for defense are prime candidates for early adoption. Replacing current infrared countermeasures systems with a high-energy laser that destroys—rather than only jamming—incoming missiles would dramatically increase survivability in semipermissive environments. Continual advances in infrared counter countermeasures (IRCCM) make current-day missiles increasingly jam resistant. The proliferation of next-generation imaging seekers further complicates this problem. Moving from a concept of infrared jamming to physical destruction of the missile, future aircraft will be able to break the cycle of incremental improvements. Destroying a small antiaircraft missile that is close to the laser-bearing aircraft takes much less laser power than an offensive system striking targets of military interest at range. For this reason, defensive systems are a good first step in building operational high-energy laser systems. Using beam-combining methods, fiber-laser assemblies are imminently scalable; their output power is limited primarily by power and cooling available on the carrier platform. With continued research funding, current limitations facing offensive laser systems will be overcome in the next decade.

Offensive laser-strike capabilities introduce a host of significant potential tactical advantages. First, fiber-laser weapons using aircraft-generated electricity have a magazine size and duty cycle limited only by onboard power-generation capability. Second, despite what Hollywood may have depicted, lasers in clear air are invisible and silent. Third, laser weapons can be incredibly precise with real-time feedback continuously optimizing the strike location. Finally, with lasers propagating at the speed of light, strike time is nearly instantaneous. Though there are yet major technical challenges to overcome, these advantages warrant continued interest. The day is not far off where an AC-130 will silently disable an adversary's ve-

hicle before a special operations raid. Silent, surgical, and persistent, laser strike provides significant options to military planners.

Another important technological advancement for airborne lasers is adaptive optics. This technology adjusts the output beam to compensate for atmospheric distortion, so after the beam propagates through the air it strikes a target with maximum focus. Traditionally, this has been done with a deformable mirror in the optical path. A wave-front sensor observes the propagated beam and uses feedback algorithms to deform the mirror until maximum intensity on target is achieved. The limiting factor in applying this technology is often the rate at which the mirror can be deformed. Even though the mirror may be able to deform many thousands of times per second, turbulent, chaotic phenomena can happen at even faster rates. Ongoing work will better characterize these flows to anticipate future conditions and feed forward corrections to the control system before they actually happen. Another method of performing adaptive optics is with phased arrays using separately controllable laser elements, as was demonstrated by the DARPA Excalibur program.

The DARPA Excalibur program significantly advanced the state of the art in high-energy lasers in several of these areas. In 2012 this program developed coherent optically phased arrays to enable scalable laser weapons. Using low-power, electrically driven, fiber-laser arrays, high beam quality was achieved through atmospheric turbulence. This was done in a form factor that was 10 times lighter and more compact than existing chemical-laser systems. Excalibur paved the way for ongoing research. Also, a systems-integration approach is being used to determine actual duty cycles, power draw, and cooling cycles for current systems.

Airborne lasers have in the past been the recipients of significant investment with little payoff.[13] Understandably, some senior leaders are skeptical that the technology is mature enough or that this time will be different. Fiber lasers with beam-combining and adaptive optics address many of the past concerns that sidelined previous work. The primary hurdle in realizing fielded systems at this point is a lack of vision. Building on recent successes, this is a medium-risk investment with a potentially high pay off as DARPA and AFRL continue to develop directed energy technologies. Building awareness in the operational community is critical to technology transition and adoption and operational concept development. Lasers present a novel weapons class. Work must be done to understand limitations and potential. The technology is now advanced enough that it is

hard to imagine a future battlespace where lasers will not play a critical role. With this in mind, tactics, doctrine, and public policy should be developed now to pave the way for this inevitable future. Critical work being accomplished now at DARPA and AFRL must continue while tactical communities work through the operational ramifications of adding these new capabilities. Directed energy will be a major component of the future battlespace. That future must be considered in terms of operational employment, strategic policy, and international law. The means to that end are well on the way to being crafted today in labs across the nation.

Conclusion

The march of technology and world events present US armed forces with a myriad of significant challenges—and parallel opportunities. Each generation of military evolution has greatly increased lethality and survivability of individual weapons platforms but has also had a corresponding rise in unit cost. To address geographic flexibility and to provide capability to overwhelm layered defenses, large numbers of low-cost platforms provide a compelling alternative. Global economic trends and domestic pressures that constrain resources allocated to military spending lead to a unique moment where change is a strong imperative. By seizing this imperative, a radically different force structure could emerge that is more effective, less expensive, and carries less risk. Current work at forward-looking institutions such as DARPA presents one vision of a future battlespace architecture that shows potential to realize that goal.

In general, the vector inspired by current DARPA programs shows great promise to seize the technological advantage and spur a tighter innovation cycle to address volatile threats. This vision will not happen on its own. Departing from longstanding unsustainable acquisition trends, research in disaggregated capabilities, hypersonic strike weapons, and directed energy provides an alternate route. Today we must set out on the path to this new force structure to build a force that is viable in 2030. SSQ

Notes

1. Notably outside the scope of this paper—but absolutely critical to this future vision—are space-, cyber-, and sea-based power projection; full spectrum low observability; precision navigation and timing (PNT); quantum communications and computing; integrated circuit advancements; biological enhancement; maritime technologies; manufacturing and material sciences; and others.

2. Unless otherwise cited, information presented in this article is based on the author's personal experience working on these programs within DARPA and discussions with actual DARPA program managers.

3. Norman R. Augustine, *Augustine's Laws.* (Reston, VA: American Institute of Aeronautics and Astronautics Inc., 1997), 107.

4. Aaron Mehta, "Work Outlines Key Steps in Third Offset Tech Development," *Defense-News*, 14 December 2015, http://www.defensenews.com/story/defense/innovation/2015/12/14/work-third-offset-tech-development-pentagon-russia/77283732/.

5. For more information on the Gremlins program, see Daniel Pratt, "Gremlins" DARPA web site, n.d., http://www.darpa.mil/program/gremlins.

6. There is lack of consensus on what the terms *expendable*, *attritable*, and *recoverable* mean in this context. To be clear, *expendable* means a single-use munition or vehicle that is completely lost after one engagement—for example, traditional cruise missiles or a Super Coyote UAV. *Attritable* means that loss of individual members of the pack is acceptable in prosecuting a mission, and *recoverable* means that after the mission is accomplished any remaining vehicles return and are available for future missions.

7. For more information on the ALIAS program, see Daniel Pratt, "Aircrews Labor In-Cockpit Automation System (ALIAS)," DARPA web site, n.d., http://www.darpa.mil/program/aircrew-labor-in-cockpit-automation-system.

8. For more information on the CODE program, see Jean-Charles Ledé, "Collaborative Operations in Denied Environment (CODE)," DARPA web site, n.d., http://www.darpa.mil/program/collaborative-operations-in-denied-environment.

9. Lara Seligman, "Beyond the Fighter Jet: The Air Force of 2030," *Defense News*, 18 April 2016, http://www.defensenews.com/story/defense/air-space/2016/04/08/beyond-fighter-jet-air-force-2030/82767356/.

10. Richard P. Hallion, Curtis M. Bedke, and Marc V. Schanz, *Hypersonic Weapons and US National Security: A 21st Century Breakthrough* (Arlington, VA: Air Force Association, 2016), http://media.wix.com/ugd/a2dd91_b7016a5428ff42c8a21898ab9d0ec349.pdf

11. Tso Yee Fan, "Laser Beam Combining for High-Power High-Radiance Sources," *IEEE Journal of Selected Topics in Quantum Electronics* 11 no. 3 (May 2005: 567–77, doi: 10.1109/JSTQE.2005.850241.

12. Focal-plane array sensors that operate in the infrared spectrum were once the domain of relatively few specialized military labs. The arrays that could be manufactured had large pixels yielding poor resolution. They were produced in small batches and were prohibitively expensive. Due to advancements in integrated chip technology, it seems likely that many of these challenges will be overcome in the next decade, leading to widespread proliferation of high-resolution, inexpensive focal-plane array infrared sensors.

13. Jason D. Ellis, *Directed-Energy Weapons: Promise and Prospects* (Washington, DC: Center for a New American Security, April 2015), https://www.cnas.org/sites/default/files/publications-pdf/CNAS_Directed_Energy_Weapons_April-2015.pdf.